Reliability oriented LBB concept for ASME Class 1 small diameter pipings

Zdarek J., Pecinka L.
Nuclear Research Institute Rez plc, Czech Republic

ABSTRACT

The deterministic LBB concept is not applicable to small diameter piping (ID < 200 mm) since the main criterion concerning stability of postulated through wall crack against plastic collapse cannot be met fully for all cross-sections of the analyzed piping. In the paper is presented the reliability based LBB concept and the following problems are discussed
- acceptable minimum safety margin
- the reliability based design criterion
- establishing of operation criteria.

All derivation are based on the IAEA recommendations for PSA studies and on the ASME Code, Section III, Article NB 3653 requirements.

1) INTRODUCTION

Safety authorities request that owners of all operating plants or plants under construction must perform analyses of ASME Class 1 pipings inside containment against effects of postulated pipe break. The corresponding guides as Standard Review Plan (SRP), chapter 3.6 [1] has deterministic character and don’t respect all uncertainties influenced the results of analyses. The probabilistic approach is partly formulated only for LBB methodology: in SRP section 3.6.3 is stated that for all pipings which fulfil the LBB requirements the probability of pipe break is extremely low but the numerical value is not specified. In general, accepted value is 10⁻⁶/reactor/year but this is not explicitly stated in SRP 3.6.3 [2].

Unfortunately the deterministic LBB concept is not applicable to small diameter pipings (ID < 200 mm) since the main criterion concerning stability of postulated through wall crack against plastic collapse cannot be met fully for all cross-sections of the analyzed piping. For the formulation of the reliability (risk) based criteria the following issues must be addressed

i) what value of annual probability of unacceptable performance is acceptable?
ii) what minimum safety margin is acceptable?
iii) what design criteria should be established to reasonably achieve the safety margin
defined under issue ii?
iv) what operation criteria should be established to support the safety margin defined under issue ii?
The first issue is purely a policy decision and is not addressed in this paper. Each of other three issues are addressed.

2) ACCEPTABLE MINIMUM SAFETY MARGIN

The following considerations are based on two recommendations for PSA studies, by IAEA [3].
i) Acceptable maximum probability of core melting is $10^{-4}$/reactoryear
ii) all postulated initiating events (PIE) with probability of exceedance less than $10^{-7}$/reactoryear may be neglected.
The small diameter pipes with ID < 200 mm are either the small boron pipes, high pressure emergency core cooling pipes or lines for cleaning treatment of primary coolant. Since this piping is obvious from stainless steel let us suppose that the failure mode is only plastic collapse. Applying the net section collapse theory, the general safety demand may be expressed as

$$\overline{\sigma}_\ell = \overline{\sigma}_{\text{nom}} + \overline{\sigma}_{\text{SSE}}$$

(1)

where $\overline{\sigma}_\ell$ is the median value of the flow stress, $\overline{\sigma}_{\text{nom}}$ represents the median of the axial stresses due to normal operating modes, i.e. inner pressure, dead weight, transients (including stratification effects) and $\overline{\sigma}_{\text{SSE}}$ represents the median value of the elastic computed seismic response. After rearrangement of equation (1) one obtain the expression for safety margin in the form

$$\overline{F}_{\text{SM}} = \frac{\overline{\sigma}_\ell - \overline{\sigma}_{\text{nom}}}{\overline{\sigma}_{\text{SSE}}} \overline{F}_{\text{NL}} \overline{F}_{\text{SSE}} = \overline{F}_C \overline{F}_{\text{NL}} \overline{F}_{\text{SSE}}$$

(2)

where $\overline{F}_C = (\overline{\sigma}_\ell - \overline{\sigma}_{\text{nom}})/\overline{\sigma}_{\text{SSE}}$ represents the median value of the pipe capacity factor, $\overline{F}_{\text{NL}}$ represents the median value of the nonlinear factor due to the ductility and $\overline{F}_{\text{SSE}}$ represents the median value of the conservatism due to the seismic calculations.
The logarithmic standard deviation (variability) $\beta$ of the safety margin can be defined by

$$\beta = \left[ \beta_C^2 + \beta_{NL}^2 + \beta_{SSE}^2 \right]^{1/2}$$

(3)

where $\beta_C$, $\beta_{NL}$ and $\beta_{SSE}$ define the variability of the capacity, nonlinear and safety factor, respectively.
In general the nature of the variability is due by the uncertainties (used mathematical models, input data, results of measurements, used statistical models for evaluation of median values) and randomness (material properties, seismicity as the random process).
If we suppose that the conditional probability of pipe plastic collapse may be expressed in the form [4]
\[ P_1 = \Phi \left( \frac{\ln \frac{1}{F_{SM}}}{\beta} \right) \]  

(4)

where
\( \Phi \) standard Gaussian cumulative distribution function
\( \ln \) natural logarithm

and that the probability of the SSE occurrence \( P_2 \) is \( P_2 = 10^{-4} \text{/year} \), than for the postulated probability of the collapse \( P = P_1 P_2 = 10^{-7} \text{/reactoryear} \)

one can obtain \( P_3 = 10^{-3} \text{/reactoryear} \) and after using of the statistical tables one can obtain the minimal value of median of safety margin \( F_{SM} = 16 \). Based on our experiences, the numerical value of logarithmic standard deviation was supposed \( \beta = 0.8 \). Since the Central Europe is not seismic active, the median value of the conservatism due to seismic calculations is approximately \( F_{SSS} = 2.0 \) and since for the standard stainless steels the nonlinear (ductility) factor \( F_{NL} = 2.0 \), as a result we obtain that the minimal acceptable safety margin value is

\[ \bar{F}_C = \frac{M_L - M_{NOS}}{M_{SSS}} \geq 4 \]  

(5)

3) DERIVATION OF THE RELIABILITY BASED DESIGN CRITERION

The US NRC Generic Letter GL 87-11 [5] demand for ASME Code, Section III, Class 1 piping that breaks and cracks need not be postulated

i) for fluid system piping in containment penetration areas

- the maximum stress range between any two loads sets (including zero load set) should not exceed \( 2.4 \) \( S_n \) and should be calculated by Eq. (10) in NB-3653 ASME Code, Section III, i.e.

\[ \sigma = C_1 \frac{P_o D_o}{2L} + C_2 \frac{D_o}{2I} M_i + C_3 E_{ab} (\alpha_a T_a - \alpha_b T_b) \leq 2.4 S_n \]  

(6)

- if the calculated maximum stress range of Eq. (5) exceeds \( 2.4 S_m \), the stress ranges calculated by both Eq. (12) and Eq. (13) in Article NB 3653, i.e.

\[ \sigma = C_2 \frac{D_o}{2I} M_i \leq 2.4 S_m \]  

(7)

and

\[ \sigma = C_1 \frac{P_o D_o}{2L} + C_2 \frac{D_o}{2I} M_i + C'_2 E_{ab} (\alpha_a T_a - \alpha_b T_b) \leq 2.4 S_n \]  

(8)
in areas other than containment penetration breaks should be postulated at the following locations in each piping and branch run

- at terminal ends
- at intermediate locations where the maximum stress range as calculated by Eq. (10) of ASME Code, Section III, NB 3653 exceeds 2.4 \( S_m \)
- at intermediate locations where the cumulative usage factor exceeds 0.1

Since all above mentioned equations are influenced by the uncertainties and randomness as defined in previous section, the reliability reformulation must be performed. First of all, for the calculated stress ranges are evaluated median values \( \bar{\sigma} \) and standard deviations \( \Delta \sigma \). If we suppose that for all this quantities the Gaussian distribution function is valid, than the \( \bar{\sigma} + (\Delta \sigma) \) denote the 84% non-exceedance probability (NEP). In the next step the break reliability index \( ri_b \) expressed as

\[
ri_b = \frac{2.4 \bar{S}_m - (\bar{\sigma} + (\Delta \sigma))}{\Delta S_m}
\]

is calculated for analyzed piping or branch run. In equation (8) \( \bar{\sigma} \) represents the stress calculated according relations (6) to (8), \( (\Delta \sigma) \) and \( (\Delta S_m) \) represents the related standard deviations. According [5] the design criterion must fulfill the condition \( ri_b \geq 1 \).

In order to relate the reliability index \( ri_b \) to minimal safety margin \( F_c \) as defined in chapter 2, the following rearrangement equations (6), (8) and (9) is made

- for the stress index \( C_i \) following condition is valid \( C_i = 2B_i \)
- for the analyzed pipings the last term in equations (6) and (8) may be neglected.

After this simplifications equations (5) and (7) take the form

\[
2\bar{\sigma}_{\text{nom}} + 2\Delta \sigma_{\text{nom}} + 0.5 \bar{\sigma}_{\text{sse}} + 0.5 \Delta \sigma_{\text{sse}} < 2.4 \bar{S}_m - \Delta S_m
\]

Since for austenitic steels \( 2.4 \bar{S}_m \approx \bar{\sigma}_f \), equation (9) may be rewritten in following form

\[
\frac{\bar{\sigma}_f - \bar{\sigma}_{\text{nom}}}{\sigma_{\text{sse}}} \geq \frac{\bar{\sigma}_{\text{nom}}}{\sigma_{\text{sse}}} - 0.5 + \frac{\sum \Delta \sigma + \Delta S_m}{\sigma_{\text{sse}}}
\]

Taking into account the minimal acceptable safety margin \( F_c = 4 \) according equation (5) of chapter 4, one may write

\[
4.5 \geq \frac{\bar{\sigma}_{\text{nom}}}{\sigma_{\text{sse}}} + \frac{\sum \Delta \sigma + \Delta S_m}{\sigma_{\text{sse}}}
\]

where \( \sum \Delta \sigma \) represents sum of the standard deviations for \( \sigma_{\text{nom}} \) and \( \sigma_{\text{sse}} \).

As the partial conclusion of this chapter may be stated that reliability based design criteria tees the form of equations (9) and (11) and that the minimum acceptable safety margin demand is taken into account.
4) ESTABLISHING OF OPERATION CRITERIA

Based on the SRP 3.6.3 three independent leak detection system must be installed. All conditions are identical with the standard LBB concept, the additional demand is the performing of reliability analysis of installation, it means the developing of the tree of events and tree of faults. The possibility of the false signal must be taken into account.

CONCLUSION

The concept of the reliability oriented LBB concept for ASME Class 1 pipings have been developed. Based on the assumption that the value of annual probability of unacceptable performance is defined by the safety authorities (i.e. probability of pipe break), the methodology for the calculation of demanded minimum safety margin is developed. Based on the ASME Code, Section III, Article NB 3653 requirements, the design criteria were established. Finally, the reliability oriented demands on the installed leak detection system were formulated. If all above formulated conditions are fulfilled, the pipe breaks need not be postulated and the pipe whip restraints need not be installed.

REFERENCES

1. US NRC. Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping, NUREG-0800


339